INTEGRAL STUDIES OF NONTHERMAL EMISSION FROM THE SUPERNOVA REMNANTS CASSIOPEIA A, CTA 1, AND MSH 11-61A

S. J. Sturner[1,2], V. Beckmann[1,3], A. Bykov[4], F. Lebrun[5], and R. Terrier[5]

[1]NASA Goddard Space Flight Center, Code 661, Greenbelt, MD 20771, USA
[2]Universities Space Research Association, 7501 Forbes Blvd., Suite 206, Seabrook, MD 20706-2253, USA
[3]Joint Center for Astrophysics, Dept. of Physics,University of Maryland, Baltimore County, MD 21250, USA
[4]AF Ioffe Institute for Physics and Technology, St. Petersburg, Russia
[5]CEA-Saclay/DAPNIA, Gif sur Yvette, France

ABSTRACT

We present the initial results from our study of the nonthermal continuum emission from the supernova remnants Cassiopeia A, MSH 11-61A, and CTA 1. We used the *INTEGRAL* Core Program data to conduct this study. During the *INTEGRAL* mission a significant fraction of the total observing time (e.g. 35% in year one) is allocated to the Core Program and is analyzed under the auspices of the *INTEGRAL* Science Working Team. We report no statistically significant detections thus far but we will continue to analyze the data as more is taken. The results so far are consistent with previous measurements from e.g. *RXTE* and *ASCA*.

Key words: ISM: supernova remnants - Gamma rays: observations.

1. INTRODUCTION

We present the initial results of our search for nonthermal X-ray and gamma-ray emission from the supernova remnants (SNRs) Casssiopeia A (Cas A), CTA 1, and MSH 11-61a using the first year of *INTEGRAL* Core Program (CP) data.

Nonthermal X-ray emission at or above 10 keV has been reported for several young SNRs. In some cases, e.g. SN1006 (Koyama et al. 1995), Cas A (Allen et al. 1997), RX J1713.7-3946 (G347.3-0.5) (Pannuti et al. 2003), and IC 443 (Sturner, Skibo, Dermer, & Mattox 1997), this emission is thought to be an indication that cosmic rays are being shock accelerated locally to TeV energies, while in other SNRs, e.g. CTA 1 (Slane et al. 1997) and MSH 11-62 (Harrus, Hughes, & Slane 1998), it is thought to arise from a central pulsar or pulsar-driven synchrotron nebula. The detection of X-rays from TeV electrons from SNRs is seen as the first step in proving that SNRs are the sources of Galactic cosmic rays below the "knee" at $\sim 10^{14}$ eV.

2. OBSERVATIONS

The data analyzed for this paper are from the *INTEGRAL* Core Program (CP). The data rights for this data belong to the *INTEGRAL* Science Working Team (ISWT). The CP is composed of the Galactic Central Radian Deep Exposure (GCDE), Galactic Plane Scans (GPS), and pointed observations of specific targets such as the Vela region. The GPS consists of a series of overlapping sawtooth pattern slew and stare maneuvers. The analyses presented here used GPS data taken between spacecraft revolutions 25 and 92. We will continue to re-analyze the CP data as more is taken. The total exposure will thus increase significantly over the life of the mission.

3. DATA ANALYSIS

The IBIS/ISGRI data were analyzed using the standard techniques as described in the IBIS Analysis User Manual available at the *INTEGRAL* Science Data Centre (ISDC). The OSA 3.0 software release was used for all steps in the analysis. The software routine ii_skyimage was used for all image extractions. The images from the individual SCWs were then mosaiced together within ii_skyimage.

The SPI data were processed using the standard techniques as described in the SPI Analysis User Manual available at the ISDC. The Offline Science Analysis (OSA) 3.0 software release was used except for the final flux extraction step. Here we used SPIROS v. 6.0 instead of the standard version 4.3.4. This new version of SPIROS has improved background handling over previous versions (Skinner & Connell 2003). SCWs that resulted in a poor χ^2 during extraction were not used in the final analysis.

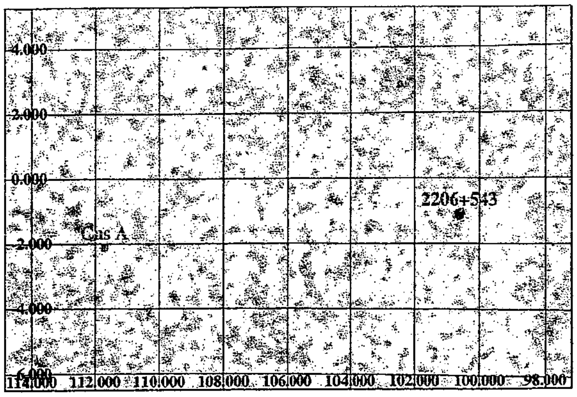

Figure 1. The IBIS/ISGRI 15-40 keV significance map for the region surrounding Cas A. There is only a marginal detection of Cas A. The pixel with the peak significance is 5σ, similar to other nearby pixels with no corresponding source.

4. RESULTS

4.1. Cas A

Cas A has an angular diameter of $\sim 5'$ and is positioned at $l = 111.74°$, $b = 2.14°$ (Green 2004) at a distance of 3.4 kpc (Reed et al. 1995). Van den Bergh & Kamper (1983), using the motions of fast moving knots in the ejecta, estimate an explosion date of 1658 ± 3. This is in rough agreement with the postulation of Ashworth (1980) who claimed that the supernova that produced Cas A was observed in 1680 by Flamsteed.

Allen et al. (1997) observed Cas A with the *Rossi X-Ray Timing Explorer* (*RXTE*) satellite. Using data from the Proportional Counter Array (PCA) and the High Energy X-Ray Timing Experiment (HEXTE), they found evidence for a "high-energy tail" in addition to the previously known low-energy thermal emission. The "high-energy tail" was found to extend to at least 60 keV and was described by a broken power law with indices $\Gamma_1 = 1.8^{+0.5}_{-0.6}$ and $\Gamma_2 = 3.04^{+01.5}_{-0.13}$ with a break energy at $E_b = 15.9^{+0.3}_{-0.4}$ keV and. This emission was interpretted as synchrotron emission from a nonthermal electron population which extends out to at least 40 TeV.

We produced IBIS/ISGRI images for individual SCWs in the 15-40 keV energy band. These individual images were then mosaiced to produce the image shown in Fig. 1. The total ontime was ~130 ksec. Given the small angular size of Cas A, 5′, and the $\sim 12'$ angular resolution of IBIS/ISGRI (Ubertini et al. 2003), Cas A should appear as a point source to IBIS/ISGRI. There is only a very marginal detection of Cas A in this energy band. The pixel with the peak significance is only 5σ and groupings of pixels with similar significance are common in the region surrounding Cas A. The significance is even lower, $\sim 2.6\sigma$, in the 40-100 keV band.

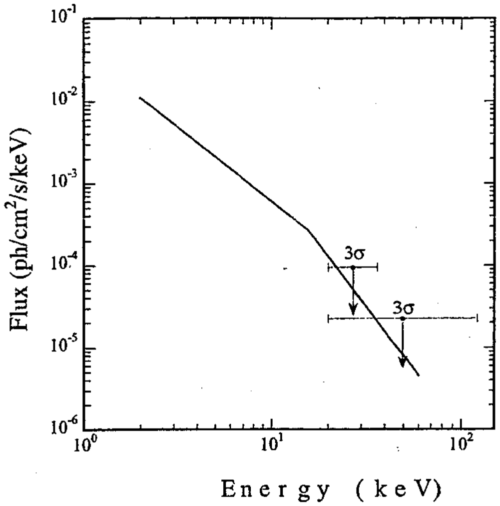

Figure 2. The 3σ SPI upper limits for the 20-36.4 keV and 20-120.7 keV energy bands. Also shown is the best-fit nonthermal model spectrum of Allen et al. (1997).

Using SPIROS, we derived 3σ upper limits in two broad energy bands: 20.0-36.4 keV and 20.0-120.7 keV from the SPI data. In Fig. 2 we show the 3σ SPI upper limits for these energy bands. Comparing these results to the best-fit nonthermal component spectrum of Allen et al. (1997) using *RXTE*, we find that the SPI upper limits are consistent with the *RXTE* results. The results so far are tantalizing but not statistically significant. Additional exposure from future GPS observations will prove valuable.

4.2. CTA 1

CTA 1 is a large ($\sim 90'$ diameter), composite SNR located well above the Galactic Plane at $l = 119.91°$, $b = 10.54°$. It exhibits radio emission from an incomplete shell (see e.g. Pineault et al. 1993, 1997) and X-ray emission from a small, centrally brightened core (Seward, Schmidt, & Slane 1995; Slane et al. 1997). The distance to CTA 1 is in the range 1.1-1.9 kpc (Sieber, Salter, & Mayer 1981; Pineault et al. 1993). The age of CTA 1 has been estimated to be from 12,400 years (Sieber, Salter, & Mayer 1981) to 20,000 years (Slane et al. 1997).

Slane et al. (1997) found, using *ASCA* GIS data, that ~60% of the 0.5-10 keV X-ray emission in a central circular region of radius 18.5′ was due to nonthermal processes. Further restricting the region of interest to a region of radius 9.2', they found that 78% of the 0.5-10 keV emission was nonthermal. The nonthermal X-ray emission from this central 9.2′ region was well fit by a powerlaw with a photon index of $2.03^{+0.05}_{-0.07}$ with no evidence for a break or cut-off below 10 keV. The integrated nonthermal X-ray flux from the central 18.5′ radius region was 2.35×10^{-11} ergs cm^{-2} s^{-1} (Slane et al. 1997)

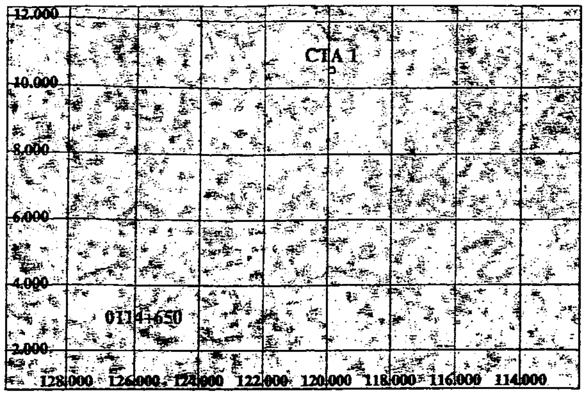

Figure 3. The IBIS/ISGRI 15-40 keV significance map for the region surrounding CTA 1. CTA 1 is not conclusively detected by IBIS/ISGRI using this data set. The peak significance near the position of CTA 1 is $\sim 2\sigma$.

Seward, Schmidt, & Slane (1995) list nine X-ray sources near CTA 1 that were unresolved by the *ROSAT* PSPC. One off these compact sources is located at the peak of the central X-ray emission. The existence of this compact source at the center of the nonthermal emission has been taken as strong evidence for a pulsar and an accompanying pulsar wind nebula (PWN) at the center of CTA 1 (e.g. Slane et al. 1997; Brazier et al. 1998). Searches for a pulsar have been conducted but with no positive results as yet (see e.g. Slane et al. 1997; Biggs & Lyne 1996; Lorimer, Lyne, & Camilo 1998).

We produced IBIS/ISGRI images for the region around CTA 1 for individual SCWs in the 15-40 keV energy band. These individual images were then mosaiced to produce the image shown in Fig. 3. The total ontime was only ~85 ksec. This is lower than for the other SNRs and is mainly due to the fact that CTA 1 is significantly above the Galactic Plane. CTA 1 is not conclusively detected by IBIS/ISGRI using this data set. The peak significance near the position of CTA 1 is only $\sim 2\sigma$.

Using SPIROS, we derived 3σ upper limits in three broad energy bands: 20.0-36.4 keV, 36.4-66.3 keV, and 66.3-120.7 keV from the SPI data. In Fig. 4 we show the 3σ SPI upper limits for these energy bands. Comparing this data to the best-fit nonthermal component spectrum of Slane et al. (1997) using *ASCA*, we find that the SPI upper limits are signifcantly above the extrapolation of the *ASCA* results. The SPI data so far do not restrict the extrapolation of the power law to beyond 120 keV.

4.3. MSH 11-61A

MSH 11-61A (G290.1-0.8) is a $19' \times 14'$ SNR located at $l = 290.14°$, $b = -0.76°$. It is a shell-type remnant in the radio but is centrally filled in the X-ray (Green 2004). Slane et al. (2002) showed that unlike CTA 1,

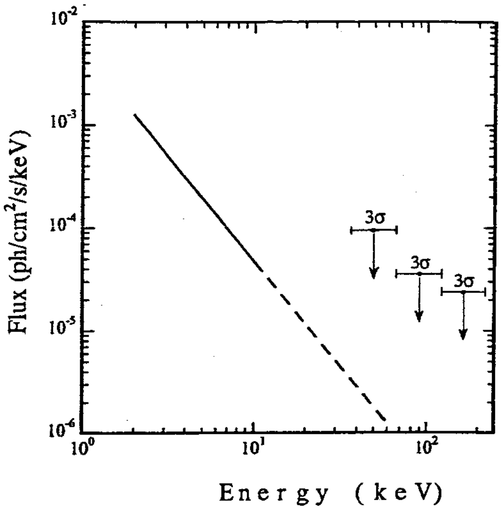

Figure 4. The SPI 3σ upper limits for the 20-36.4, 36.4-66.3, and 66.3-120.7 keV energy bands (points). Also shown is the best-fit model for the nonthermal emission of Slane et al. (1997). The dashed portion of the line is an extrapolation of the fit beyond the ASCA data used to produce it. The ASCA data are well below the SPI upper limits.

the centrally concentrated X-ray emission from MSH 11-61A is mostly thermal in origin. They found that the ratio of the thermal to nonthermal flux in the 0.5-10 keV band was ~ 82. The best-fit temperature for the thermal X-ray emission was 0.60 ± 0.03 keV and the best-fit spectral index for the nonthermal component was 1.4 ± 0.8. Slane et al. (2002) find that they can adequately model the X-ray emission of MSH 11-61A if the SNR age and distance are 1-2×10^4 years and 8-12 kpc.

A young pulsar, PSR J1105-6107, has been discovered $\sim 22'$ from the center of MSH 11-61A (Kaspi et al. 1997). This pulsar has a period of 63 ms and an estimated distance from its dispersion measure of 7 kpc. The characteristic age of the pulsar is 63,000 years. The X-ray emission from PSR J1105-6107 was characterized by a power-law spectrum with photon index 1.8 ± 0.4 with an unabsorbed 2-10 keV flux of $(6.4 \pm 0.8) \times 10^{-13}$ ergs cm^{-2} s^{-1} (Gotthelf & Kaspi 1998).

We again produced IBIS/ISGRI images for the region around MSH 11-61A for individual SCWs in the 15-40 keV energy band. These individual images were then mosaiced to produce the image shown in Fig. 5. The total ontime was ~115 ksec. Neither MSH 11-61A nor PSR J1105-6107 are detected using this dataset, the significances are actually negative near the positions of these two objects.

We were able to derived 3σ upper limits in three broad energy bands: 20.0-36.4 keV, 66.3-120.7 keV, and 120.7-219.7 keV from the SPI data. In Fig. 6 we show the 3σ SPI upper limits for these energy bands. We compare these upper limits to both the nonther-

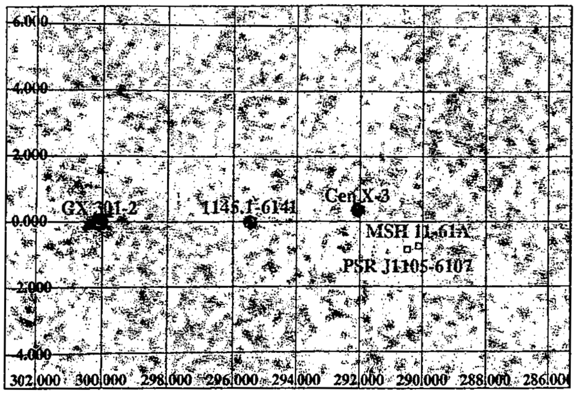

Figure 5. The IBIS/ISGRI 15-40 keV significance map for the region around MSH11-61A. Neither MSH 11-61A nor PSR J1105-6107 are detected using this dataset (peak significances in the region are < 0).

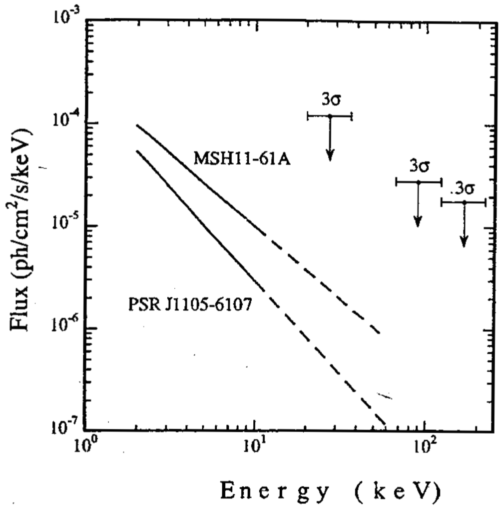

Figure 6. The SPI σs upper limits for MSH11-61A/PSR J1105-6107. Also shown are the combined best-fit model ASCA spectra (nonthermal component only) for these sources (Slane, Smith, Hughes, & Petre 2002; Gotthelf & Kaspi 1998).

mal component of the X-ray spectrum from MSH 11-61A and the spectrum observed from PSR J1105-6107. We find that the SPI upper limits are significantly above the extrapolation of the previous results. We conclude that MSH 11-61A is not detected by either SPI or IBIS/ISGRI using this dataset.

5. CONCLUSIONS

We can not yet report a stastiscally significant detection for any of these objects. The upper limits we report are consistent with the spectral results from previous missions. Of the three SNRs reported on here, it is apparent that only Cas A will be detectable by SPI given any reasonable observation time, e.g. $\lesssim$1 Msec.

REFERENCES

Allen, G. E., Keohane, J. W., Gotthelf, E. V., et al. 1997, ApJ, 487, L97

Ashworth, W. B. 1980, J. History Astron., 11, 1

Biggs, J. D., & Lyne, A. G. 1996, MNRAS, 282, 691

Brazier, K. T. S., Reimer, O., Kanbach, G., & Carraminana, A. 1998, MNRAS, 295, 819

Gotthelf, E. V., & Kaspi, V. M. 1998, ApJ, 497, L29

Green, D.A. 2004, A Catalog of Galactic Supernova Remnants (2004 January version), Mullard Radio Asronomy Observatory, (www.mrao.cam.uk/surveys/snrs/)

Harrus, I. M., Hughes, J. P., & Slane, P. O. 1998, ApJ, 499, 273

Kaspi, V. M., Bailes, M., Manchester, R. N., et al. 1997, ApJ, 485, 820

Koyama, K., Petre, R., Gotthelf, E. V., et al. 1995, Nature, 378, 255

Lorimer, D. R., Lyne, A. G., & Camilo, F. 1998, A&A, 331, 1002

Pannuti, T.G., Allen, G.E., Houck, J.C., & Sturner, S.J. 2003, ApJ, 593, 377

Pineault, S., Landecker, T. L., Madore, B., & Gaumont-Guay, S. 1993, AJ, 105, 1060

Pineault, S., Landecker, T. L., Swerdlyk, C. M., & Reich, W. 1997, A&A, 324, 1152

Reed, J. E., Hester, J. J., Fabian, A. C., & Winkler, P. F. 1995, ApJ, 440, 706

Sieber, W., Salter, C. J., & Mayer, C. J. 1981, A&A, 103, 393

Seward, F. D., Schmidt, B., & Slane, P. 1995, ApJ, 453, 284

Skinner, G., & Connell, P. 2003, A&A, 411, L123

Slane, P., Smith, R. K., Hughes, J. P., & Petre, R. 2002, ApJ, 564, 284

Slane, P., Seward, F. D., Bandiera, R., Torii, K., & Tsunemi, H. 1997, ApJ, 485, 221

Sturner, S. J., Skibo, J. G., Dermer, C. D., & Mattox, J. R. 1997, ApJ, 490, 619

Ubertini, P., Lebrun, F., Di Cocco, G., et al. 2003, A&A, 411, L131

van den Bergh, S., & Kamper, K. W. 1983, ApJ, 268, 129